Numerical Simulation of Coastal Trapped Disturbances along the U.S. West Coast

Peter L. Jackson
Environmental Studies Program, The University of Northern British Columbia
3333 University Way
Prince George, British Columbia
CANADA, V2N 4Z9
phone: (250) 960-5985; fax: (250) 960-5539 or 5538; email: peterj@unbc.ca

Chris J. C. Reason
School of Earth Sciences, University of Melbourne
Parkville
Victoria 3052
Australia
phone: 61 3 9344-6907; fax: 61 3 9344-7761; email: cjr@met.unimelb.edu.au

Award # N00014-97-1-0342
http://nimbus.unbc.ca

LONG-TERM GOALS

The long-term goal of this research is to better understand and explain the initiation, propagation and demise of trapped atmospheric disturbances in the coastal marine boundary layer, particularly those which have been observed to occur along the US West Coast. In particular we wish to obtain a better understanding of how topographic variability along the west coast of North America influences the evolution, propagation, and decay of Coastal Trapped Disturbances (CTD). Emphasis is placed on examining the termination of events which observations to date suggest may occur in the vicinity of bends, such as Cape Mendocino and Cape Blanco. A secondary objective is to determine whether a reduced gravity model (applied to these events in previous work) is a good approximation of the coastal atmosphere during CTD events. It is anticipated that this improved understanding will lead to enhanced forecasting of CTD and their impact.

OBJECTIVES

Our proposed research has the objective of determining firstly, what forces CTD generation, secondly, what the fundamental dynamics responsible for CTD generation are, thirdly, how topographic variability along the U.S. west coast influences CTD propagation and demise, fourthly, the sensitivity of CTD propagation and evolution to variability in surface heating and frictional gradients, and lastly, whether a reduced-gravity approximation of the atmospheric stratification and wind distributions is a reasonable assumption. These objectives build on those originally proposed and take into account some of the important theoretical and observational findings made during the previous few years by various members of the ARI.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **Numerical Simulation of Coastal Trapped Disturbances along the U.S. West Coast**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The University of Northern British Columbia,Environmental Studies Program,3333 University Way ,Prince George, British Columbia Canada, V2N 4Z9,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

The major tool being used to address the above objectives is the Colorado State University Regional Atmospheric Modeling System (RAMS), a 3D mesoscale numerical model which is used in two modes, namely idealized and realistic simulations. Idealized simulations with simplified topography and initial conditions are most easily interpreted, can be compared most directly with analytic models, and can be used for parameter sensitivity tests. They are limited however because the CTD simulated must be specifically inserted into the model. This is problematic given that there does not appear to be a canonical CTD structure: they have been described as both single and combined manifestations of trapped gravity currents, Kelvin waves, and as down-gradient acceleration due solely to synoptic pressure forcing (e.g. Dorman, 1985, 1987; Mass and Albright, 1987).

Secondly, realistic simulations of observed events with realistic topography, and with observed horizontally and temporally variable initial and boundary conditions are used. These simulations can provide information on forcing mechanisms, internal dynamics and propagation characteristics of observed CTD events. A force balance analysis of model results after Jackson and Steyn (1994) tells us about CTD initiation and propagation characteristics for a specific event. We have simulated the May 1985 event whose characteristics, based upon sparse observations, have been documented in the literature (Mass and Albright, 1987).

WORK COMPLETED

A number of 2- and 3D RAMS simulations have been performed with idealized configurations to investigate the sensitivity of an idealized coastal trapped disturbance to changes in background synoptic conditions and topography. The background synoptic changes have included: wind speed, stratification (inversion height strength and depth), initiation mechanism (low-level cooling), sea-surface temperature, and sea breeze strength. The topographic changes have involved: coastal mountain gaps (valleys) of various magnitudes, coastal mountains of varying slope, and the presence of bends in the mountains and coastal islands (Reason, Jackson and Fu, 1999; Fu, Reason and Jackson, 1997).

A RAMS configuration with three nested grids, realistic topography and nudged towards NCEP analyses at the boundaries of the coarsest grid has been used to simulate an observed CTD event. The particular event chosen was that of May 15-17 1985 observed (Mass and Albright, 1987) along the Northern California and Pacific North West coast, since this was an event whose dynamics were relatively straightforward to interpret and which lead to relatively intense and abrupt weather changes in the coastal zone. The first paper from this study (Guan, Jackson and Reason, 1998) validated the simulation against available observational data, and concluded that RAMS can be successfully applied to further understanding of these events. The second part of the study (Jackson , Reason and Guan, 1999) has improved the MBL representation and analyzed detailed diagnostics from the simulation with the aim of isolating the fundamental processes important in the initiation, propagation and demise of this event.

The third and fourth parts of this study (Tory, Jackson and Reason, 1999; and Tory, Reason and Jackson, 1999) have assessed the influence of topography, surface properties and local circulations on CTD evolution and decay for the May 1985 realistic event. In order to do this, mountain heights, the presence or absence of mountains and islands, sea surface temperature, surface fluxes, etc., are adjusted and the CTD response quantified. In the fifth part of this study (Reason, Tory and Jackson,

1999) realistic simulations of the May 1985 event were compared to the idealized CTD model presented in Skamarock, Rotunno and Klemp (1999), and the similarities and differences discussed.

RESULTS

Idealized simulation results of gravity current-like CTD suggest that they are quite sensitive to the size and intensity of the initiating cold pool. Large cold pools with large amounts of cooling of a scale which allows geostrophic adjustment to take place, result in CTD which decay more rapidly than those initiated with smaller cooling areas. If the cooling amount or area is too small however, the supply of cold air becomes the limiting factor and the CTD will also decay more rapidly. Sea surface temperature values similar to those of the cold pool seem to enhance propagation speed and are associated with idealized CTD which exhibit sharp surface transitions. When coastal mountains are less steep, onshore flow is not blocked as effectively and the CTD response is weaker (Fu, 1999). These idealized simulation results are in agreement with the realistic CTD simulations in which topography was varied (Tory, Jackson and Reason, 1999). The idealized simulations further reveal that CTD stall and weaken with a reduction in across-shore scale, when they propagate past gaps in the coastal mountains. Wider, deeper gaps cause more attenuation. Idealized simulations with a near-shore island reveal that there is a trapped response on both the mainland coastal mountains and on the island (Reason, Jackson and Fu, 1999; Fu, Reason and Jackson, 1997).

Analysis of the initiation stage of the realistic simulation of the May 15-18, 1985 event suggested that synoptically driven offshore flow ahead of the CTD and deceleration of onshore flow of relatively cool, marine air by the coastal mountains in the Southern California Bight were important for initiation. The time scales and force balances diagnosed in the numerical simulation were consistent with theory presented in Reason and Steyn (1992) and Reason (1994). The along-shore propagation of the event was essentially that of a coastally trapped gravity current, in semigeostrophic balance, at least during the later part of its life-cycle, again consistent with the theory and with the observations of Mass and Albright (1987). Demise of the event near the northern tip of Vancouver Island occurred once favorable synoptic forcing no longer existed; however, the detailed force balances involved were complex and varied at different locations on the coast with advective and diffusive contributions significant (Jackson, Reason and Guan, 1999).

A tool to quantitatively assess the intensity of a CTD and allow comparison between simulations, has been developed. This tool, an example of which is shown in Figs. 1, is a latitude vs. time contour plot of the meridional potential temperature gradient in a coast-parallel transect near the surface. It is a useful way of characterizing CTD intensity and propagation characteristics: the zone of maximum meridional potential temperature gradient marks the CTD leading edge; the slope of this leading edge position is the propagation speed; the CTD intensity is related to its potential temperature gradient and propagation speed.

The event depicted in Fig. 1 initiates around hour 30, rapidly propagates north until hour 40 when it appears to change its characteristics and move more slowly north until hour 72 when it begins to decay. This change in slope of the locus of maximum potential temperature gradient (in other words a change in propagation speed) is interpreted as a change in dynamical character of the disturbance from a mixed Kelvin wave/bore to a trapped gravity current (Reason, Tory and Jackson, 1999). The location and timing of this change in speed and character of the disturbance is shown to be closely tied to local circulations driven by the diurnal heating cycle (Reason, Tory and Jackson, 1999) (Fig. 1) and to local mesoscale topographic variability (Tory, Reason and Jackson, 1999). The diurnal heating cycle is

necessary to create the alongshore temperature gradients needed for CTD propagation and initiation (Fig. 1b). Additionally, CTD propagation and initiation characteristics are found to be strongly modulated by the diurnal cycle, with propagation and initiation favored during the night. Suppression of the MBL by offshore advection ahead of the disturbance is found to be important in creating alongshore temperature and pressure gradients that are favorable for CTD initiation and propagation. It is suggested that the MBL suppression process ahead of the CTD is the gradual downslope migration of the lee-mountain separation point that is initially dependent upon the local Froude number. As geostrophic adjustment takes place, the migration of the separation point becomes dependent upon the ratio of the Rossby number to the Froude number. Spatial variations in the local Froude number leading to spatial variations in MBL suppression can result in formation of a small-scale CTD (Tory, Reason and Jackson, 1999) in certain circumstances.

IMPACT/APPLICATIONS

The realistic simulations represent some of the very few attempts to model the initiation, propagation and demise of an actual event. It has now been demonstrated that a 3D mesoscale numerical model can be used to study in detail the evolution of particular events, providing that the data used to initialize the model and as lateral boundary conditions are of sufficiently good resolution. The NCEP analyses, even though they don't resolve the MBL, appear to satisfy this requirement, at least for strong CTD events where synoptic forcing rather than internal boundary layer dynamics dominate. If the nudging from NCEP analyses is eliminated in inner grids of the mesoscale model, then the mesoscale model can develop a reasonable MBL as shown in our publications following Guan, Jackson and Reason (1998).

The results of our modeling work, in combination with the work of others in the coastal meteorology ARI, has lead to an understanding of the main mechanisms for initiation and propagation, as well as the unsteady propagation due to complex terrain of CTD along the North American west coast. Since the models appear to represent the main features of CTD quite well, this lends confidence to their application in other geographic locations where perhaps less validation data exists.

These results provide guidance for future modeling and forecasting efforts by the community as well as further understanding of CTD in general.

TRANSITIONS

Since the significant results of our research are just now being published, it is too soon to see direct applications of our work by others.

RELATED PROJECTS

Between August 1994 and August 1995, Jackson has been PI in an observational program designed to detect CTD along the Beaufort Sea coastline between Barrow Alaska and the MacKenzie River. Four pressure and temperature measuring devices were deployed between Prudhoe Bay and Shingle Point to supplement the existing meteorological network. Analysis and digital filtering of the data has found several likely CTD, and one event that very closely resembles a non-linear Kelvin Wave ridge. Jackson has continuing funding from the Canadian Natural Science and Engineering Research Council and Atmospheric Environment Service, part of which supports modeling and analysis of CTD along the British Columbia Coast.

The Australian Research Council has funded Reason to investigate the characteristics of CTD in southeastern Australia. With lower topography and generally less pronounced stratification in southeastern Australia than in California, conditions are not as favorable for CTD events there. However, there are several documented cases of pronounced coastal weather changes associated with the propagation of a coastally trapped ridge. Other cases appear to be more related to the enhancement in the coastal zone by the topography of the weather associated with the passage of a cold front (Southerly Busters). RAMS has been applied to diagnose the characteristics of the CTD event of Nov 9-11, 1982 (Holland and Leslie, 1986) that brought rapid and severe weather changes along the Australian coast from near Melbourne to Brisbane (Reason, Tory and Jackson, 1999; Tory, Reason and Jackson, 1999 in preparation).

We will be mounting a small field program utilizing a network of surface stations and a doppler sodar system, during the summer of 2000 to monitor the propagation of CTD past the Juan de Fuca Strait on the North American west coast. The field program will provide further information and validation data on the propagation characteristics of CTD as they pass a major gap in the coastal mountains.

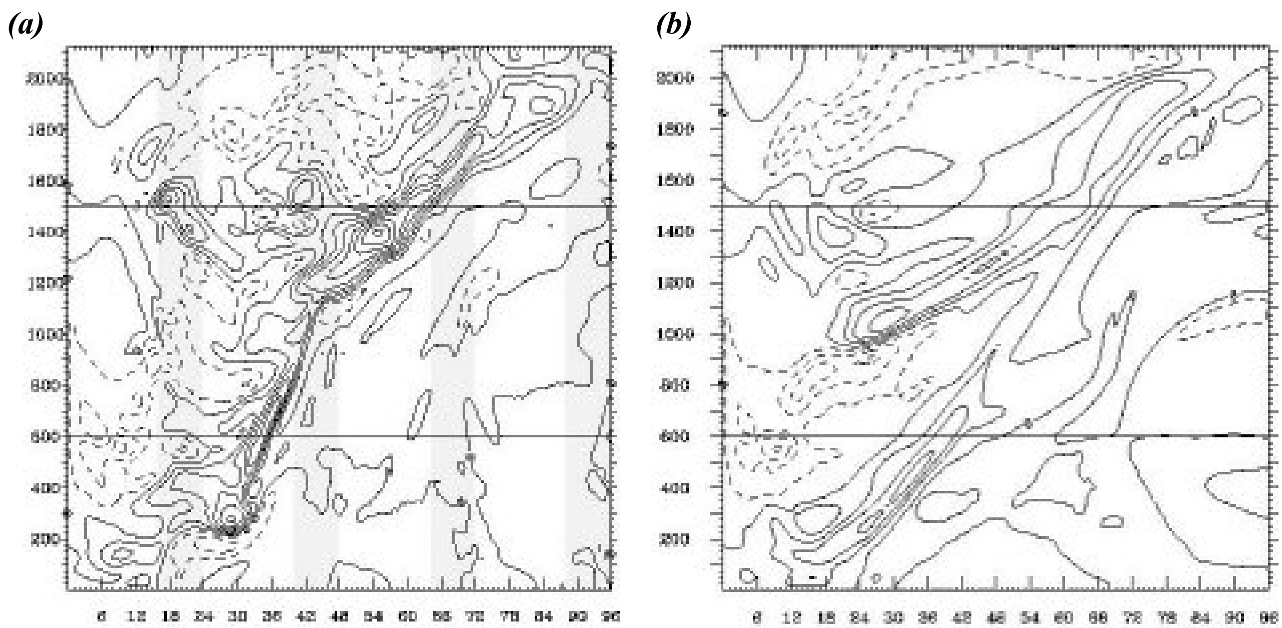

Fig. 1: Meridional potential temperature gradient in an along-coast transect during 96 hours of simulation. The y-axis is distance from south to north (km) along the North American west coast from southern California (0 km) to north of Vancouver Island (2000 km). The x-axis is time from the start of the simulation. The CTD leading edge is represented as the locus of maximum along-coast potential temperature gradient. (a) Realistic topography and radiation cycle. The shaded bands represent the 8 hours of maximum solar radiation. Notice the sharp change in slope of the locus of maximum potential temperature at hour 40 representing a transition from a mixed Kelvin wave/bore to a gravity current. Also notice the decrease in gradient during daytime hours and re-intensification at night. (b) Same as (a) except with model radiation turned off. Notice the decrease in potential temperature gradient at the CTD leading edge and the general decrease in propagation speed in (b) versus (a), illustrating the importance of diurnal effects on CTD.

REFERENCES

Dorman, C.E., 1985: Evidence of Kelvin waves in California's marine layer and related eddy generation. *Mon. Wea. Rev.*, **113**, 827-839.

Dorman, C.E., 1987: Possible role of gravity currents in Northern California's coastal summer wind reversals. *J. Geophys. Res*., **92**, 1497-1506.

Fu, H., C.J.C. Reason, and P.L. Jackson, 1997: The effects of boundary and initial conditions of idealized coastal trapped disturbance evolution. Preprints, 12th Symposium on Boundary Layers and Turbulence. Amer. Meteor. Soc., Vancouver, July 28 – August 1, pp. 350-351.

Guan, S., P.L. Jackson and C.J.C. Reason, 1998: Numerical modeling of a coastal trapped disturbance. Part I: Comparison with observations. *Mon. Wea. Rev.*, **126**, 972-990.

Holland, G.J. and L.M. Leslie, 1986: Ducted coastal ridging over South East Australia*. Quart. J. Roy. Met. Soc*., **112**, 731-748.

Jackson, P.L., D.G. Steyn, 1994: Gap winds in a fjord. Part I: Observations and numerical simulation. *Mon. Wea. Rev*., **122**, 1245-1265.

Mass, C.F. and M.D. Albright, 1987: Coastal southerlies and alongshore surges of the West Coast of North America: Evidence of mesoscale topographically trapped response to synoptic forcing. *Mon. Wea. Rev*., **115**, 1707-1738.

Reason, C.J.C., and R. Dunkley, 1993: Coastally trapped stratus events in British Columbia. *Atmosphere-Ocean*, **31**, 235-258.

Reason, C.J.C. and D.G. Steyn, 1992: The dynamics of coastally trapped mesoscale ridges in the lower atmosphere. *J. Atmos. Sci*., **49**, 1677-1692.

Reason, C.J.C., 1994: Orographically trapped disturbances in the lower atmosphere: scale analysis and simple models. *Met. Atmos. Phys*., **53**, 131-136.

Skamarock, W.C., R. Rottuno and J.B. Klemp, 1999: Models of coastally trapped disturbances. *J. Atmos. Sci. in press.*

PUBLICATIONS

Direct publications during FY 1999

Fu, H., 1999: Numerical simulations of coastally trapped disturbances. MSc. Thesis, University of Northern British Columbia.

Jackson, P.L., C.J.C. Reason, S. Guan, 1999: Numerical modeling of a coastal trapped disturbance. Part II: Structure and dynamics. *Mon. Wea. Rev.*, **127**, 535-550.

Nuss, W.A., J. Bane, W. Thompson, C. Dorman, A.M. Ralph, R. Rotunno, J. Klemp, W. Skamarock, R. Samelson, A. Rogerson, C.J.C. Reason, P.L. Jackson, 1999: Coastally trapped wind reversals: A new level of understanding from the experiment on coastally trapped disturbances. *accepted Bull. Amer. Meteor. Soc.*

Reason, C.J.C., K.J. Tory, and P.L. Jackson, 1999: Models of coastally trapped disturbances: Validation from realistic simulations. *submitted to J. Atmos. Sci.*

Reason, C.J.C, P.L. Jackson, and H. Fu, 1999: Influence of large valleys on the propagation of coastally trapped disturbances and applications to forecasting and air quality. *accepted Meteorological Applications.*

Tory, K.J., P.L. Jackson, and C.J.C. Reason, 1999: Sensitivity of CTD dynamics to barrier height and topographic variability in a numerical model. *submitted to Mon. Wea. Rev.*

Tory, K.J., P.L. Jackson, and C.J.C. Reason, 2000: Sensitivity of CTD dynamics to barrier height and topographic variability in a numerical model. paper presented at 7th Australian Meteorological

and Oceanographic Society National Conference and 5th Australian Conference on the Physics of Remote Sensing of the Atmosphere and Ocean, Melbourne, Australia, 7-9 February 2000

Tory, K.J., C.J.C. Reason, and P.L. Jackson, 1999: The influence of lee-mountain waves on marine boundary layer dynamics in a numerical model and the generation of a coastally trapped disturbance. *submitted to Mon. Wea. Rev.*

Closely related publications during FY 1999

Reason, C.J.C., K.J. Tory, and P.L. Jackson, 1999: Numerical simulation of a coastal trapped disturubance in southeast Australia. Part I: Observations and model validation. *accepted Meteor. Atmos. Phys.*